Progress on the Development of a RF Driven D⁻ Ion Source for ITER NBI

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Introduction

• Results from BATMAN in 2005
  • Modified LAG Grid System
  • Parameter Dependencies
  • Experiments on Magnetic Confinement

• Comments on Cs introduction

• Initial Hα – Beam Spectroscopy Results
## BATMAN Performance Compared to ITER Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER Requirement</th>
<th>BATMAN Hydrogen</th>
<th>BATMAN Deuterium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Density H</td>
<td>28 mA/cm²</td>
<td>33 mA/cm²</td>
<td>---</td>
</tr>
<tr>
<td>Current Density D</td>
<td>20 mA/cm²</td>
<td>---</td>
<td>23 mA/cm²</td>
</tr>
<tr>
<td>Electron - Ion Ratio</td>
<td>&lt;1</td>
<td>0.36</td>
<td>0.9</td>
</tr>
<tr>
<td>Source Pressure</td>
<td>0.3 Pa</td>
<td>&lt;0.3 Pa</td>
<td>&lt;0.3 Pa</td>
</tr>
<tr>
<td>Extraction Voltage</td>
<td>9 kV</td>
<td>9.6 kV</td>
<td>9.9 kV</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>3600 s</td>
<td>4 s</td>
<td>4 s</td>
</tr>
<tr>
<td>Extraction Area</td>
<td>2000 cm²</td>
<td>70 cm²</td>
<td>70 cm²</td>
</tr>
<tr>
<td>RF Power</td>
<td>---</td>
<td>144 kW</td>
<td>125 kW</td>
</tr>
<tr>
<td>PG Temperature</td>
<td>---</td>
<td>197 C</td>
<td>222 C</td>
</tr>
</tbody>
</table>
The IPP NNBI RF source:

Improvement 2005:

- using a mask with chamfered holes in front of the plasma grid
  - high yield, high RF efficiency, similar for H and D
  - no dependence on grid temperature above 130 °C
    → water cooled grid possible

- more space around holes (less surfaces)
- covering holes near heating wires

minor effect (?)
Physics of a cesiated RF source:

- \( \text{H}^- \) production at the plasma grid
  - needs Cs at the surface
  - mean free path some cm’s

- extraction of surface produced negative ions
  - problem of ‘wrong’ starting angle: ions produced at the grid are accelerated by the sheath potential back into the source and have to bend back towards the grid
    - bending mechanisms: CX, collisions, magnetic fields
    - bad beam quality

  - mask with chamfered holes
    - increases effective converter area in immediate vicinity of ex hole
    - increases solid angle for incoming \( \text{H}^0 \)
    - improves „starting angles“ of \( \text{H}^- \) leaving grid surface

\[ \text{H}^0, \text{H}^+ + \text{surface e} \rightarrow \text{H}^- \]

> few eV

> 15 eV (RF)
The IPP NNBI RF source: Low Pressure / Cs Operation: Daily Results

Results 2005:

- low pressure (0.2 – 0.5 Pa)
- extraction voltage up to 10.5 kV
- RF power < 130 kW
- 3 – 6 seconds

- cal. current density well above 28 mA/cm\(^2\) (Hydrogen) / 20 mA/cm\(^2\) (Deuterium) routinely achieved

- electron/ion ratio ≤ 1

- best results:
  - 33 mA/cm\(^2\) H \(j_e/j_H = 0.5\)
  - 25 mA/cm\(^2\) D \(j_e/j_D = 1.3\)
  - 23 mA/cm\(^2\) D \(j_e/j_D = 0.9\)
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- ‘fast’ recovery after leak
The IPP NNBI RF source: ITER Parameters

19 Pulses ok!
Low Pressure / Cs Operation:
Parameter Dependence: RF Power

RF power:

- no saturation with RF power, if Cs distribution o.k.
- Deuterium, $U_{ex} 9.5 \text{ kV}$, $<0.5 \text{ Pa}$
- ‘RF efficiency’:
  \[ \frac{j}{P_{RF}} \]
- reduces data scatter
The IPP NNBI RF source: RF Efficiency

Results 2005:

- low pressure (0.2 – 0.5 Pa)
- extraction voltage up to 10.5 kV
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- RF efficiency ever higher for D
- differences due to different magnetic configuration of the ion source
- D needs more extraction voltage
- performance is limited by limitations in total / extraction voltage & in the power onto the extraction grid
Low Pressure / Cs Operation: Operation at low pressure

Low pressure operation: pressure drop in driver

- RF coupling not efficient for high RF power when driver pressure is too low
- pressure drop increases with RF power, decreases with extraction area (larger gas flow)
  - better coupling at high RF powers for large sources → more current density!

18 mA/cm² onto cal.
Filling pressure: 0.27 Pa
IPP RF source: Magnetic Confinement

- flexible modification of filter field and side wall confining magnets

- side wall confining magnets influence filter field
- changing filter field effects plasma dynamics (→ Cs!)
General Behavior:

- Source can operate without side wall confining magnets (\( j_{D^-} = 18 \text{ mA/cm}^2 \))
- Deuterium needs more filter field than hydrogen for electron suppression
  - up to now only possible with outside magnets
  - far-reaching field into the source
  - limits RF power coupling \( \rightarrow \) reduces RF efficiency
- Filter field has minor effect on source efficiency
- Next experiments with more localized filter field (near grid)
The IPP NNBI RF source: Cs Behaviour

Improvement of RF source with Cs (2004/5):

- increase of current density by a factor 10
- hot plasma grid (~150 °C)
- reduces amount of co-extracted electrons $< 1$
  (together with 10-15 V positive bias and sufficient filter field)

ITER requires reliable Cs seeded operation

- Cs seeded source subject to “De-conditioning”
- To achieve a properly conditioned Cs seeded source:
  - slow evaporation works best (10 mg/h)
  - look for signs that Cs on PG is “sufficient”:
    - electron current falls, ion current rises

- This requires Patience!

- diagnostic tools for more understanding (see talk of U. Fantz)
$\Delta \lambda = \lambda \cdot \frac{\alpha}{\psi}$

- measurement of stripped atoms leaving the accelerator
- depends on grid optics
- main stripping in first gap
**Hα Spectroscopy: Stripping Losses**

- **low stripping:**
  \[ \dot{J}_{\text{cal}} = \dot{J}_{\text{extracted}} \]
  (assume all D- have full energy)

- **Calculation:**
  - only conductance of grids
  - gas temperature of 300 K
  - but source: 1000 – 1200 K

- **same model as used in ITER stripping loss calculations**
  - ITER calculations may be too pessimistic?
    - modelling with trajectories for stripping losses in the grid necessary
Summary

- exceed all ITER objectives except pulse length simultaneously on BATMAN
  - $>22 \text{ mA/cm}^2$ in deuterium, $>30 \text{ mA/cm}^2$ in hydrogen
  - at $I_{\text{elec}}/I_{\text{ion}} < 1$ and at pressures below 0.3 Pa in driver and filling pressure
- reliable and reproducible operation over 3 months
- even higher source efficiency for deuterium
- stronger filter required for Deuterium: modifications under way
- wall confinement affects source efficiency

- deuterium operation is limited by
  - power on extraction grid due to higher electron ion / ratio
  - RF coupling at low pressures due to pressure drop in driver and far-reaching filter fields

larger sources and modified filter fields:
- increase in RF power possible
- expect same current densities for Deuterium as for hydrogen!
• **Electrical Currents are all measured:**
  - $I_{ion}$ gives $J_{ion}$ (elec)
  - $I_{elec}$
  - $I_{GG}$ gives $J_{ion}$ (GG)

• **Calorimeter signals give $J_{ion}$ (TC) and $J_{ion}$ (W)**

• $J_{ion}$ (TC) and $J_{ion}$ (W) are systematically different
  - Likely the flow meter is slightly off

• **Accountability: $J_{ion}$ (TC) to $J_{ion}$ (elec) $\approx$ 90%**.
Beam extraction: BATMAN

**HV Power Supply**

- **$U_{HV}$**
- **$I_{drain}$**

**Plasma Grid**

- **$I_{EG} (e)$**
- **$I_{gg} (ions)$**
- **$I_{ion} (ions)$**

**Extraction / e Suppression Grid**

**Grounded Grid**

**Calorimeter with Spatial Resolution**

**Tank**

- **$H^-$**
- **$i_{ion}$**
- **$j_{cal}$**
Spectroscopy on the Cs 852 nm Line

Before start of first Cs evaporation after source modifications

After start of Cs evaporation (4 mgr evaporated)
Electric vrs Calorimetric Current Densities

Electric $J_{H^{-}}$ (mA cm$^{-2}$)

$J_{\text{electric}} = J_{\text{ion (electric)}} - J_{\text{ion (G3)}}$

$J_{\text{cal}} = 0.92 J_{\text{electric}}$